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An updated MILES stellar library and stellar population models (Research Note)

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ABSTRACT

Aims. We present a number of improvements to the MILES library and stellar population models. We correct some small errors in the radial velocities of the stars, measure the spectral resolution of the library and models more accurately, and give a better absolute flux calibration of the models.

Methods. We use cross-correlation techniques to correct the radial velocities of the offset stars and the penalised pixel-fitting method, together with different sets of stellar templates, to re-assess the spectral resolution of the MILES stellar library and models. We have also re-calibrated the zero-point flux level of the models using a new calibration scheme.

Results. The end result is an even more homogeneously calibrated stellar library than the originally released one, with a measured spectral resolution of ~ 2.5 Å, almost constant with wavelength, for both the MILES stellar library and models. Furthermore, the new absolute flux calibration for the spectra excellently agrees with predictions based on independent photometric libraries.

Conclusions. This improved version of the MILES library and models (version 9.1) is available at the project's website (<http://miles.iac.es>).

Key words. catalogs – methods: data analysis – techniques: spectroscopic – stars: kinematics and dynamics – galaxies: kinematics and dynamics

1. Introduction

The MILES library consists of 985 stars spanning a large range in atmospheric parameters (Sánchez-Blázquez et al. 2006a, hereafter S06). The spectra were obtained at the 2.5 m Isaac Newton Telescope at the Observatorio del Roque de los Muchachos and cover the range 3525–7500 Å with an originally estimated spectral resolution of 2.3 Å full-width half maximum (*FWHM*). A homogenized compilation of the stellar atmospheric parameters (T_{eff} , $\text{Log}(g)$, $[\text{Fe}/\text{H}]$) for the stars of this library was presented in Cenarro et al. (2007). Four years after its release, MILES has proved to be an often used, well calibrated stellar library that has been extensively used for a wide range of different applications (Davis et al. 2007; Emsellem et al. 2007; Shields et al. 2007; Martins & Coelho 2007; Cenarro et al. 2008; Scelsi et al. 2008; Zuckerman et al. 2008; Cid Fernandes & González Delgado 2010). The stellar library is also the basis for our empirical models for stellar population synthesis (Vazdekis et al. 2010, hereafter V10). Both the stellar library and models can be easily accessed and manipulated through our dedicated website: <http://miles.iac.es>.

During the last year, we have had some private communications with different research groups reporting that some stars in the stellar library showed radial velocities different from zero. We have explored this question and, indeed, confirmed these

offsets. In this research note, we summarize our solution for this problem and also the re-assessment of the spectral resolution for the stellar library and models, which had also been questioned. While sorting out these concerns, we also addressed the absolute (but not the relative) flux scaling for our model spectra. Updated versions of both datasets are available from our website.

2. MILES stellar library

2.1. Radial velocity corrections

Some stars in the originally released version of the stellar library (v9.0) are not at rest with respect to the Sun. In order to correct from this effect we cross-correlated each star with a high-resolution solar spectrum from the BASS2000 database¹. This cross-correlation was performed across wavelength in intervals of 250 Å width. The resulting velocities were fitted, as a function of wavelength, with a fifth order polynomial, which was used to de-redshift the spectra. The cross-correlation using the solar spectrum as a template only gives us accurate velocities for solar-type stars. For the rest, we used as a templates MILES stars with similar spectral types that were already corrected from the velocity offsets. We divided the stars into 15 broad groups as a function of their atmospheric parameters so that

¹ http://bass2000.obspm.fr/solar_spect.php

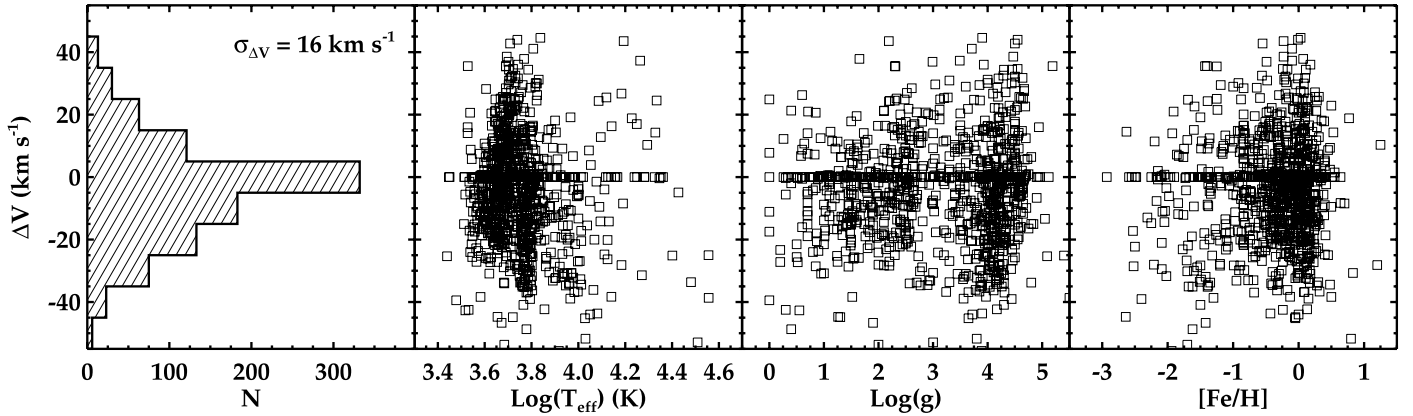


Fig. 1. Histogram with the mean velocity difference (averaged over the whole wavelength range) for stars between the originally released MILES stellar library (v9.0) and the corrected version presented here (v9.1). The dispersion of the histogram ($\sigma_{\Delta V}$) is also indicated. Offsets are also presented as a function of atmospheric parameters: effective temperature ($\text{Log}(T_{\text{eff}})$), surface gravity ($\text{Log}(g)$), and metallicity ($[\text{Fe}/\text{H}]$).

only 15 stars were used as templates for the whole library. This is a compromise between trying to avoid the template mismatch and the propagation of the errors that result from using one corrected star as a template to correct another.

Figure 1 shows a histogram with the mean velocity differences between the MILES stars published in 2006 (v9.0) and the new, corrected ones (v9.1). The figure indicates that 50% of the stars in the library were affected by this problem (at least beyond the expected wavelength calibration uncertainties, on average 10 km s^{-1}). We note and explain below that these offsets have very little impact on the resulting spectral resolution for our single stellar population models (hereafter SSPs). The average dispersion for the sample ($\sigma_{\Delta V} = 16 \text{ km s}^{-1}$) is indicated. The figure also shows the lack of dependence of these offsets on a particular set of stellar parameters. The list of stars with the corrections will be posted on the MILES website.

2.2. Re-assessment of the spectral resolution

The data employed to re-assess the resolution of the MILES stellar library consists of three sets of spectra (for each version of the library: v9.0 and v9.1):

1. *HD 010307*: a star in the MILES stellar library with stellar parameters ($T_{\text{eff}} = 5838.0$, $\text{Log}(g) = 4.28$, $[\text{Fe}/\text{H}] = 0.03$) very similar to those of the Sun, assumed here to have $T_{\text{eff}} = 5770$, $\text{Log}(g) = 4.4$, and $[\text{Fe}/\text{H}] = 0.0$.
2. *Fake_Sun*: best representation of the solar spectrum obtained by combining solar-type stars in our library using the interpolation scheme described in Vazdekis et al. (2003) for the Sun parameters above.
3. *MILES stars*: the 985 spectra from the MILES stellar library. In order to avoid template mismatch effects derived from limitations of the different template libraries, we have also selected a subset of 55 stars with stellar parameters close to those of the Sun (i.e. where most libraries are assumed to be reliable) for some of the tests.

The stellar libraries used as templates are

1. *Sun (KPNO)*: observed solar spectrum obtained from the National Solar Observatory Atlas (Kurucz et al. 1984). The spectrum covers the wavelength range between 2970 and 9530 Å with a resolution of $R \sim 300\,000$.
2. *Indo-US library*: empirical library downloaded from <http://www.nao.edu/cflib/>. It consists of 1273 stars

observed with the 0.9 m Coudé Feed telescope at Kitt Peak National Observatory. The spectra typically cover from 3454 to 9469 Å, with a nominal spectral resolution ($FWHM$) of $\approx 1.2 \text{ Å}$ (Valdes et al. 2004). For our tests, only spectra without gaps in the wavelength regions covered by the MILES dataset were used (193 stars).

3. *ELODIE (v3.1) library*: the ELODIE library includes spectra for 1388 stars obtained with the ELODIE spectrograph at the Observatoire de Haute-Provence 193 cm telescope in the wavelength range 390 to 680 nm. The library used here is at $R = 10\,000$. Details of the library can be found in Prugniel & Soubiran (2001).
4. *S⁴N library*: the *Spectroscopic Survey of Stars in the Solar Neighbourhood* (S⁴N, Allende Prieto et al. 2004) is a library with a complete spectroscopic catalogue of stars with spectral types brighter than K2V within 15 parsec from the Sun. The resulting database contains high-resolution optical spectra for 118 nearby stars (mostly dwarfs) at $R \sim 60\,000$ from 3600 to 9200 Å. See <http://leda.as.utexas.edu/s4n/>
5. *Coelho theoretical library*: this is the only theoretical library used in our tests. It contains stellar spectra for different effective temperatures ($3500 \leq T_{\text{eff}} \leq 7000 \text{ K}$), surface gravities ($0.0 \leq \text{log}(g) \leq 5.0$), metallicities ($[\text{Fe}/\text{H}] = -0.5, 0.0, 0.2$), and chemical compositions ($[\alpha/\text{Fe}] = 0.0$ and 0.4). Spectra were retrieved from <http://www.cruzeirodosul.edu.br/nat/modelos.html>, and are described in Coelho et al. (2005) and Coelho et al. (2007). The models have a nominal spectral resolution of 1.0 Å ($FWHM$) and cover the wavelength range between 3000 Å and 13 000 Å.

We measured the broadening of the different datasets using the penalized pixel-fitting (pPXF) method of Cappellari & Emsellem (2004), with the data and templates described above. Before running pPXF, both the data and templates were rebinned to a common velocity scale of 25 km s^{-1} . A non-negative linear combination of those templates, convolved with a Gaussian, was fitted to each individual test spectrum. The best-fitting parameters were determined by chi-squared minimization in pixel space. In order to assess the dependence with wavelength, we divided the original datasets into seven bins. Additionally, a low-order Legendre polynomial (order 5) was included in the fit to account for small differences in the continuum shape between the test spectra and the input templates.

Before carrying out the desired tests on the MILES library, we tested whether we were able to reproduce the quoted spectral

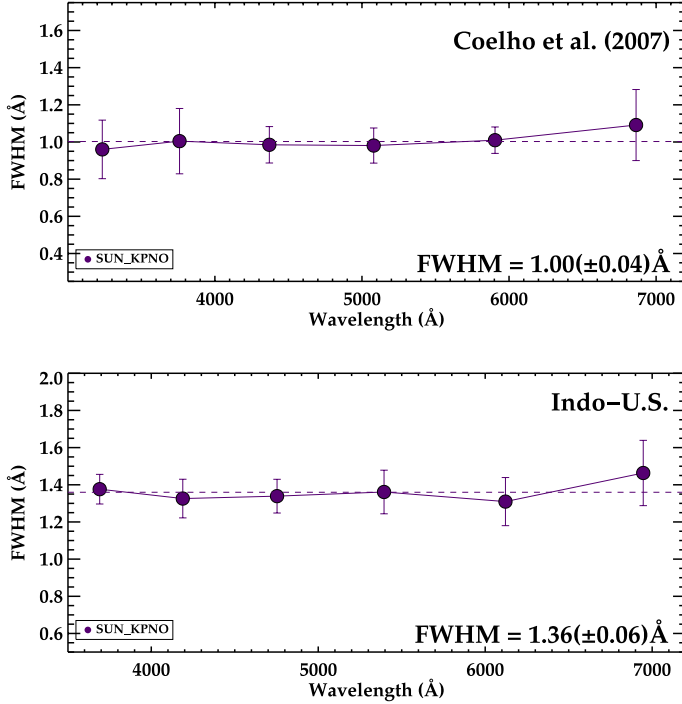


Fig. 2. Measured spectral resolution of the Coelho et al. (2007) and Indo-US libraries. A small subset of the libraries (i.e. spectra with parameters close to the Sun) were used for this test. We used the solar spectrum from KPNO as template.

resolution of the Indo-US and Coelho’s libraries using the stars with stellar parameters closest to the Sun. Given that they have $FWHM$ relatively close to the expected values for MILES, knowing the real value is important to avoid systematic offsets in the measured resolution. The other libraries have such high spectral resolution that an error in the exact value has very little impact in our results. The outcome of our tests are shown in Fig. 2. The plot confirms that the spectral resolution of Coelho’s library is indeed 1.0 Å , while it shows that for Indo-US it appears to be slightly higher, $FWHM = 1.36(\pm 0.06) \text{ Å}$, than the approximate value estimated by the Indo-US team ($\approx 1.2 \text{ Å}$). For internal consistency, we adopt 1.36 Å in our analysis. We note that in S06 we measured a $FWHM$ of 1.0 Å for the Indo-US library based on much simpler tests. The difference between the two values is at the centre of the new spectral resolution quoted in this research note, which is reinforced by the use of other template stellar libraries.

After assessing the true spectral resolution of the Coelho and Indo-US libraries we proceeded to determine the resolution of the MILES library using the test cases proposed above. These tests were carried out for the original and updated versions of the library and models.

1. *MILES single star: HD 010307.* This is the most basic test we conducted. In this case we tried to derive the spectral resolution of the MILES stellar library from a single star. The star was chosen for having stellar parameters very close to those of the Sun. The results in Fig. 3 show some scatter as a function of wavelength, where the regions around $H\beta$ and $H\alpha$ are the noisiest ones. The measured $FWHM$ is very similar in both versions $\sim 2.55(\pm 0.08) \text{ Å}$. It is worth noting that results obtained using the Sun as template yields worse results than those coming from libraries where several templates

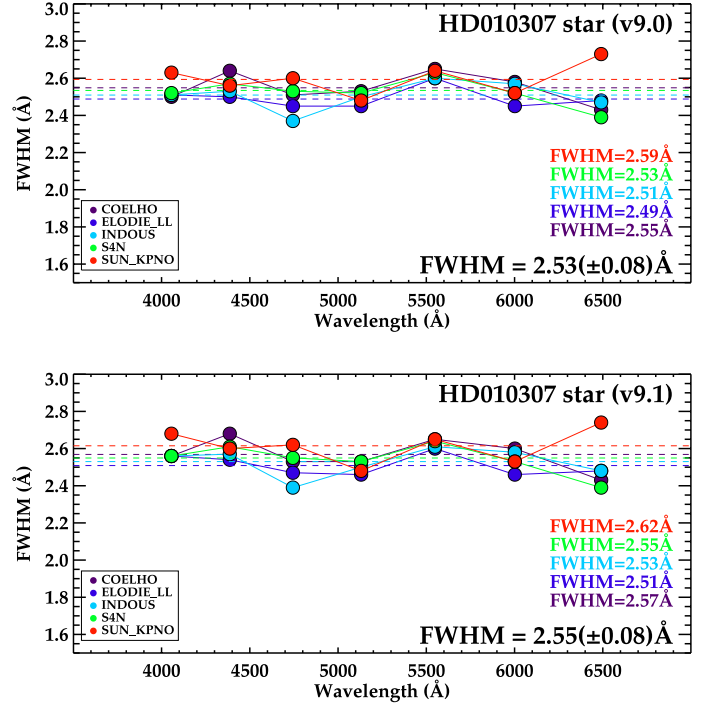


Fig. 3. Measured spectral resolution of the HD 010307 spectra for both versions. HD 010307 is a star in the MILES stellar library with stellar parameters: $T_{\text{eff}} = 5838.0$, $\text{Log}(g) = 4.28$, $[\text{Fe}/\text{H}] = 0.03$.

have been used to derive the best fit, which highlights the importance of template mismatch in this kind of tests.

2. *MILES interpolated solar-type star: Fake_Sun.* In this test we tried to suppress the impact of template mismatch by producing a star as close as we could to the solar spectrum. We achieved this by means of the interpolation scheme described in Vazdekis et al. (2003). This spectrum is the combination of 11 stars in the MILES stellar library. Figure 4 shows the results of our tests. In general, the output values are very similar to those in the previous test, with the significant difference that the resulting $FWHM$ has now decreased to $\sim 2.49(\pm 0.08) \text{ Å}$. The comparison between this and the previous test illustrates the expected level of uncertainty produced by template mismatch (which is also reflected in our estimated errors).
3. *MILES stellar library.* The previous tests, while very instructive to assess the order of magnitude of the spectral resolution of the MILES library, are still incomplete in the sense that they might not reflect the full range of variations possible in the library. Given the large span in stellar parameters of the Coelho’s, Indo-US, and ELODIE libraries, we used the complete set of MILES stellar spectra for this exercise. For the Sun (KPNO) and S⁴N templates, we selected a small subset of stars of the MILES library with stellar parameters close to those of the Sun (55 stars) to minimise template mismatch. The outcome of this test is shown in Fig. 5. The results are quite similar to those found for the Fake_Sun. Individual typical uncertainties in the measured spectral resolution vary from 0.1 to 0.2 Å . Also, not surprisingly, the higher $FWHM$ values correspond to those libraries with the fewer number of templates (e.g. Sun (KPNO) and S⁴N).

All these tests suggest that the spectral resolution of the new version of the MILES stellar library is $2.50 \pm 0.07 \text{ Å}$, essentially constant as a function of wavelength. During the course of this

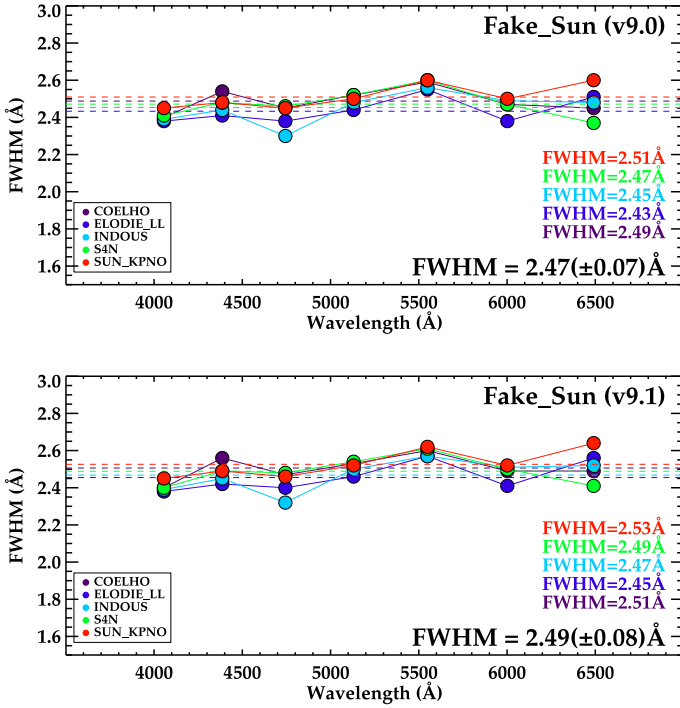


Fig. 4. Measured spectral resolution of the interpolated solar spectrum (Fake_Sun) spectra for both versions. This stellar spectrum is made of the following 11 stars in the MILES library: HD 076780, HD 186427, HD 076151, HD 010307, HD 095128, HD 186408, HD 072905, HD 020619, HD 143761, HD 141004, HD 200790.

work an independent group carried out complementary tests and reached similar conclusions (Beifiori et al. 2011).

2.3. Impact on line-strength indices

Given the shifts in radial velocity applied to the stars of the MILES library, it is important to assess how these corrections affect the line-strength indices present in our wavelength range. For this comparison we concentrated on the Lick indices (e.g. Worthey et al. 1994). Figure 6 shows the difference in the measured indices, which are in general within the errors of traditional stellar population studies (e.g. Sánchez-Blázquez et al. 2006b). For reference, we show in the same figure the expected uncertainties for index measurements at signal-to-noise ratios of 30 and 75 \AA^{-1} (Cardiel et al. 1998).

The largest discrepancies appear in line-strength indices at shorter wavelengths, where the signal-to-noise of the stellar spectra is naturally lower (S06). The worst cases are $H\delta_F$, CN_2 , $G4300$, and $H\gamma_A$. This is caused by the overlap of their definition bands (e.g. $H\delta_F$ with CN_2 , and $G4300$ with $H\gamma_A$). The strongest differences occur when the Balmer lines are so intense (e.g. at high effective temperatures) that they start invading the blue and red pseudo-continuum of the CN_2 and $G4300$ bands respectively. Conversely, the discrepancies at the lowest values of the $H\delta_F$ and $H\gamma_A$ indices occur at the highest values of CN_2 and $G4300$ indices.

3. MILES stellar population models

3.1. Spectral resolution of the MILES models

In addition to the stellar library, we also carried out the measurement of the spectral resolution for the MILES single stellar

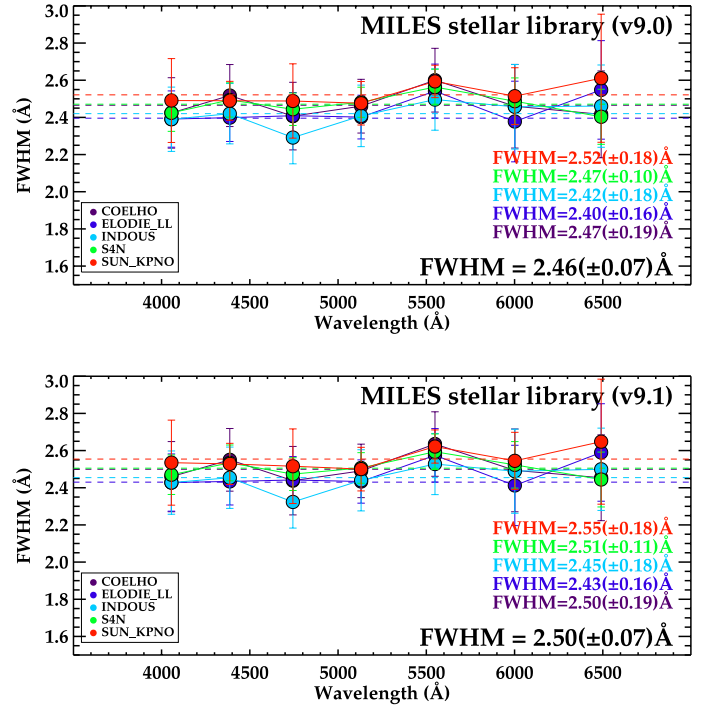


Fig. 5. Measured spectral resolution of the MILES stellar library spectra for both versions. The 985 stars in the MILES library were considered when the Coelho's, Indo-US, and ELODIE libraries are used as templates. Only stars in the library with parameters close to the solar ones were used for the Sun (KPNO) and S^4N stellar templates. The value in parentheses is the rms of the resolution for each case.

population models. These are based on the combination of MILES stars in a meaningful way (in the physical sense) following the prescriptions described in V10. For this test and to minimize template mismatch, we used Kroupa Universal SSP models with $[M/H] = [-1.31, -0.71, -0.4, +0.0, +0.22]$ and Age = $[0.5, 17]$ Gyr (160 models). This time we did not include results from the KPNO and S^4N libraries because of the significant template mismatch observed in those fits (i.e. the solar spectra did not describe the SSP models properly, and the S^4N library is mostly composed by dwarf stars and thus could not reliably reproduce the SSP spectra, where giants represent a considerable contribution to the total light in the MILES spectral range).

Given that the models are the mixture of many different types of stars (e.g. from A to M stars), one could expect the resulting $FWHM$ to be worse than that of the stellar library. Figure 7 shows that this is not the case. The end $FWHM$ is $2.51 \pm 0.07 \text{ \AA}$ and thus very similar to that of the stellar library. The agreement between the two versions of SSP models seems remarkable, given the differences in radial velocities of some stars in the stellar library (see Sect. 2.1). In order to understand this question we calculated the expected increase or decrease in spectral resolution produced by the dispersion of the velocity offsets presented in Fig. 1 ($\sigma_{\Delta V} = 16 \text{ km s}^{-1}$). It turns out that shifts of that order would affect our measurements by $\approx 0.01 \text{ \AA}$, which is within the uncertainties in our determinations, and thus have a very small effect on the final values reported here. Furthermore, the similarity of the results among libraries strongly supports our measured $FWHM$ for the Indo-US library. If a $FWHM$ of 1.2 \AA is assumed, the values reported in all tests using the Indo-US library would be lower by $\approx 0.1 \text{ \AA}$.

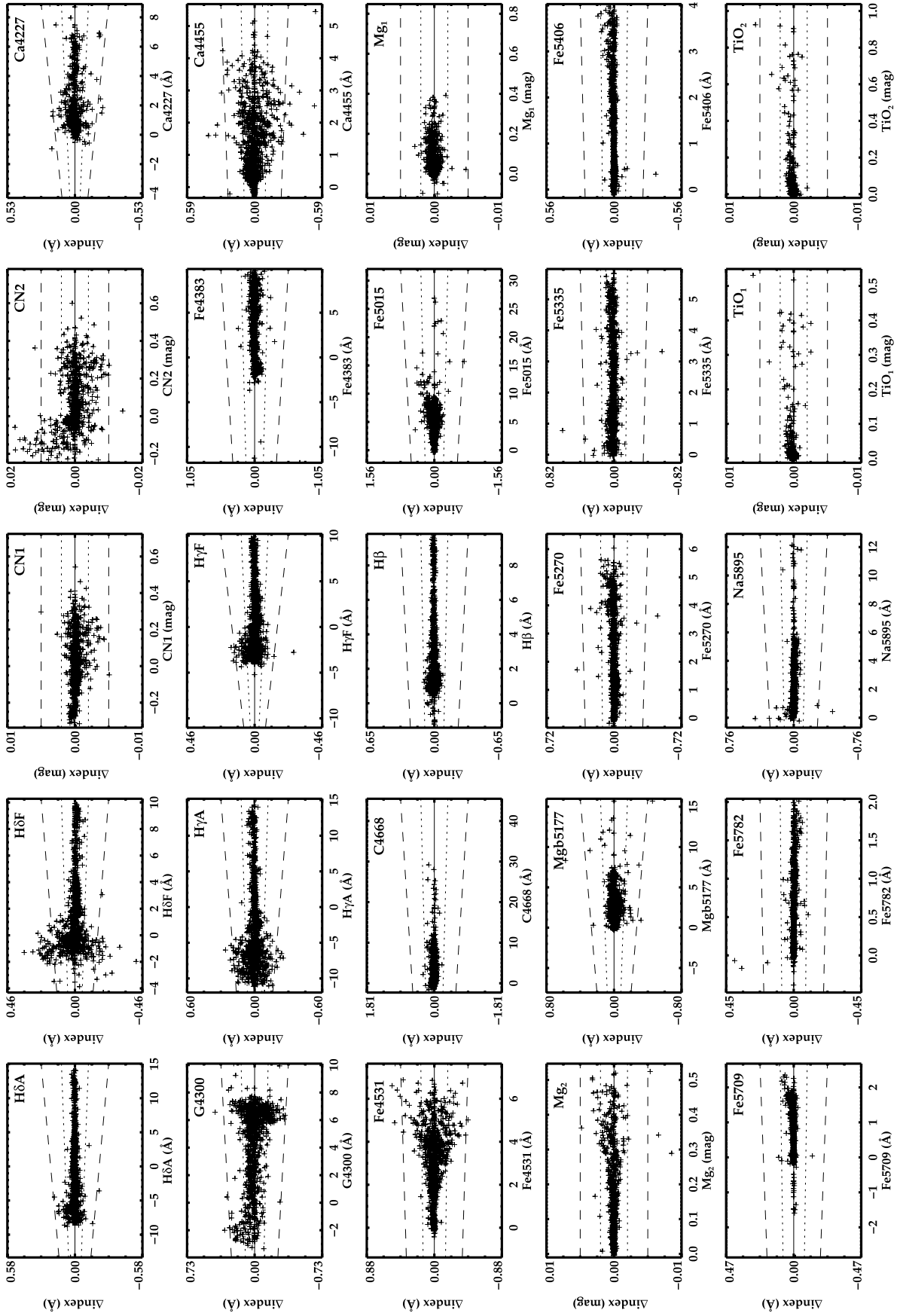


Fig. 6. Line-strength differences between versions 9.0 and 9.1 of stars in the MILES stellar library. The solid line marks the zero level. The dashed and dotted lines indicate the expected uncertainty for spectra with a signal-to-noise ratio of 30 and 75 Å⁻¹ respectively (see Cardiel et al. 1998). The vertical axis has been adjusted to twice the maximum uncertainty expected for a spectrum with a signal-to-noise ratio of 30 Å⁻¹ within the line-strength index range shown.

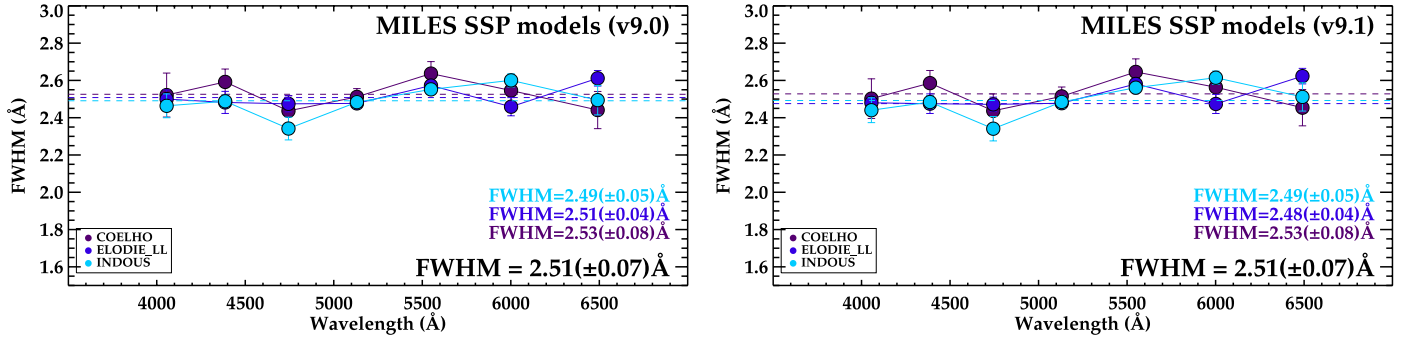


Fig. 7. Measured spectral resolution of the MILES SSP model spectra for both versions. To minimize template mismatch, we concentrated on SSP models with $[M/H] = [-1.31, -0.71, -0.4, +0.0, 0.22]$ and Age = $[0.5, 17]$ Gyr (160 models). The KPNO and S⁴N spectra were not included in this test because they do not contain enough representative stars to accurately reproduce the SSP models.

3.2. Absolute flux-calibration of the MILES models

In the updated version of the SSP models (v9.1) we also corrected a flaw detected in the absolute flux scale of the model spectra that we distributed in v9.0. The magnitudes measured on the MILES v9.0 SSPs were ≈ 0.23 mag brighter than those synthesized from our photometric approach, which employs temperature-gravity-metallicity colour relations derived from extensive photometric stellar libraries, as described in Vazdekis et al. (1996) and V10. Models with very steep initial mass functions at the low-mass end (i.e. steeper than Salpeter), however, show smaller offsets. We note that for most applications that make use of these spectra there is no significant effect, except for those inferring mass-to-light ratios directly from the model spectra.

In order to make the two predictions (i.e. the photometric and spectroscopic) consistent, we changed our scaling method when integrating the stellar spectra along the isochrone and followed the same approach as was used to derive the photometric predictions (Vazdekis et al. 1996). To determine the absolute flux in the V-band corresponding to each star, we adopted the V filter response of Buser & Kurucz (1978) and followed the method described in Fukugita, Shimasaku & Ichikawa (1995):

$$F_V = 10^{-0.4(V + Z_{pV} - V_{\alpha_{Ly\alpha}})} \quad (1)$$

where Z_{pV} and $V_{\alpha_{Ly\alpha}}$ are the adopted zero-point and V magnitude for the reference Vega spectrum, respectively. To compute the zero-point, we used the Hayes (1985) spectrum of Vega with a flux of $3.44 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$ at 5556 Å. The V magnitude of Vega is set to 0.03 mag, in concordance with the value adopted by Alonso et al. (1995), because we mostly use Alonso et al. (1996) and Alonso et al. (1999) for converting the theoretical parameters of the isochrones to the observational plane. For the integration of a stellar spectrum as requested by the isochrone, which comes from our interpolation scheme (see Vazdekis et al. 2003), we normalised the total flux in the V-band to unity by convolving with the same filter response.

With the new calibration scheme the absolute magnitudes derived directly from the spectra are fully consistent with those computed from the photometric libraries well below the observational uncertainties (≤ 0.01 mag) for all ages, metallicities, and initial mass functions. This new scaling was also applied to the SSP models based on the Calcium triplet stellar library (Cenarro et al. 2001; Vazdekis et al. 2003). It is important to remark that although the absolute flux scale of the new models has changed with respect to the older models, this has no impact on the relative flux calibration as a function of wavelength and thus synthetic colours are not affected. As shown in figure 19 of V10,

the difference between the photometric and the spectroscopic $B - V$ colour for our reference Vega system is within 0.02 mag for the safe model ranges, with a dispersion of 0.01 mag for the Kroupa initial mass function.

3.3. Impact on line-strength indices

Similarly to the stellar library, we have also compared the predicted line-strength indices for the two versions of the SSP models. Figure 8 shows this comparison for the Kroupa Universal IMF. The differences between the two sets of models are naturally much smaller than those found for the individual stars, given that the models are a combination of many different types of stars. It is interesting to note the small discrepancies observed in the CN₂ and G4300 indices, which follow the reasons given in Sect. 2.3 for the stars. These results show that the impact of the radial velocity corrections on the SSP model line-strength indices is generally small compared with typical observational uncertainties.

4. Conclusions

In this report we summarize our efforts to improve on a number of minor problems identified in both the MILES stellar library and models. We have corrected some stars in the stellar library for radial velocity offsets with respect to the solar rest frame and checked that they have a small impact on the resulting line-strength indices of the stars and models. We also re-assessed the spectral resolution of the MILES library and models, confirming that it is quite constant as a function of wavelength. We established that the new values are 2.50 ± 0.07 Å for the stellar library and 2.51 ± 0.07 Å for the models. We also changed the scheme used to flux calibrate the spectra in the absolute sense. As a result we find an excellent agreement (≤ 0.01 mag) between fluxes measured from our spectra and those from predictions obtained by using photometric (rather than spectroscopic) libraries. Our tests also show that the spectral resolution of the Indo-US library is slightly higher ($FWHM = 1.36 \pm 0.06$ Å) than the approximate value established by the Indo-US team ($FWHM \approx 1.2$ Å).

The updated version of the MILES stellar library and models in this research note (version 9.1) supersede those presented in S06 and V10 and are available at the MILES website (<http://miles.iac.es>). This new set of spectra sets the basis for forthcoming papers describing the extension of our model predictions to other wavelength ranges.

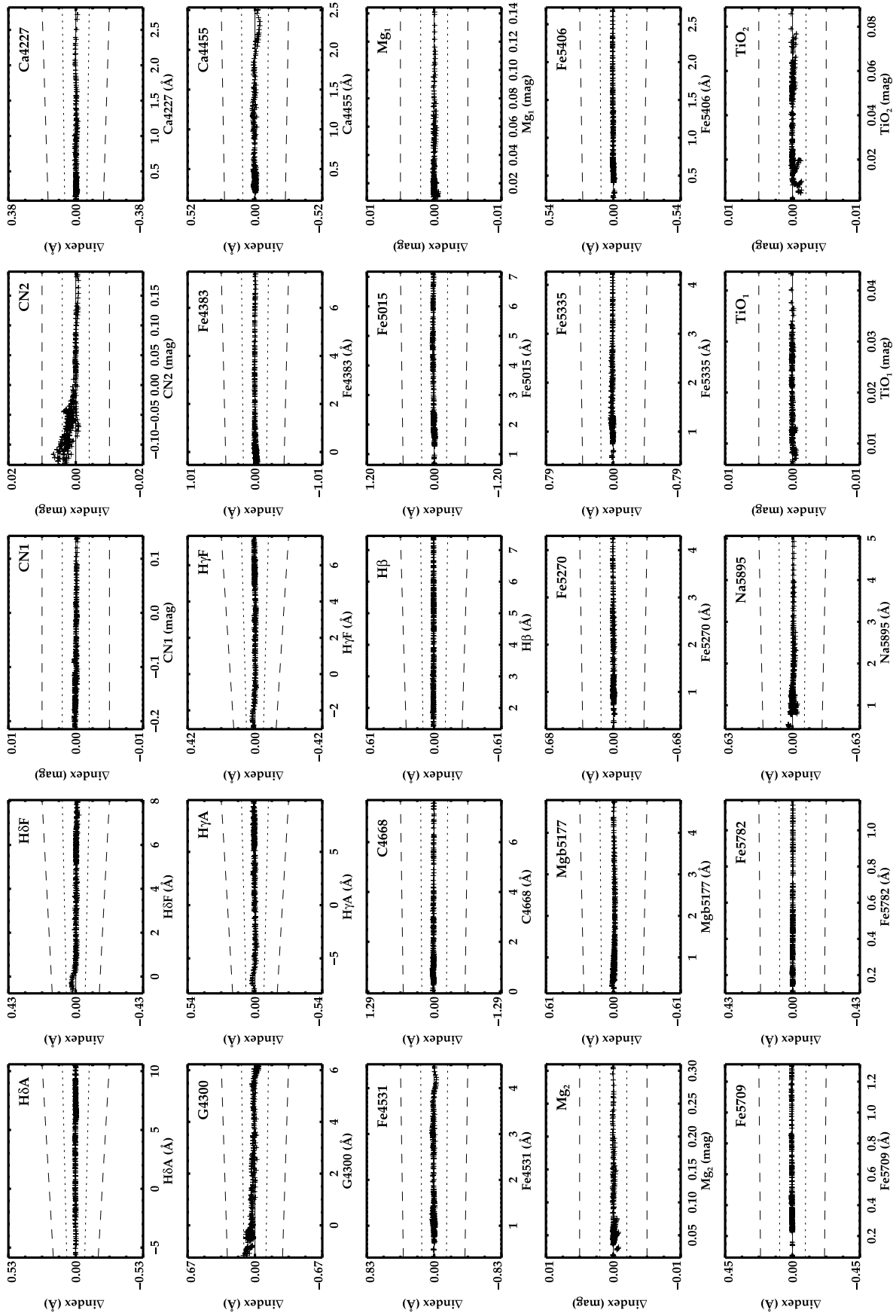


Fig. 8. Line-strength differences between versions 9.0 and 9.1 of the MILES SSP models with a Kroupa Universal IMF. Solid line marks the zero level. Dashed and dotted lines indicate the expected uncertainty for spectra with a signal-to-noise ratio of 30 and 75 \AA^{-1} , respectively (Cardiel et al. 1998). The vertical axis was adjusted to twice the maximum uncertainty expected for a spectrum with a signal-to-noise ratio of 30 \AA^{-1} within the line-strength index range shown.

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